Simultaneous Magneto-Optical Trapping of Two Lithium Isotopes

Marc-Oliver Mewes, Gabriele Ferrari, Florian Schreck, Alice Sinatra, and Christophe Salomon
Laboratoire Kastler Brossel, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris CEDEX 05, France
(February 9, 2008)

We confine 4×10^8 fermionic ^{6}Li atoms simultaneously with 9×10^9 bosonic ^{7}Li atoms in a magneto-optical trap based on an all-semiconductor laser system. We optimize the two-isotope sample for sympathetic evaporative cooling. This is an essential step towards the production of a quantum-degenerate gas of *fermionic* lithium atoms.

PACS: 32.80.Pj

The observation of Bose-Einstein condensation in atomic vapors [1] has made dilute *bosonic* quantum gases experimentally accessible and the study of these systems has since been very fruitful. Quantum degenerate gases of neutral *fermionic* atoms such as ^{6}Li or ^{40}K have so far not been studied experimentally. At temperatures below the Fermi temperature in such systems energy and momentum transfer is modified by Fermi statistics [2,3]. One striking example would be the partial suppression of spontaneous emission in an atomic Fermi gas [4]. Also, a Fermi gas of neutral atoms in a mixture of different hyperfine (HF) states might undergo a BCS pairing transition and exhibit long range coherence and superfluid behavior [5]. It could give access to phenomena so far only observed in strongly interacting Fermi systems such as atomic nuclei, the quantum liquid ^{3}He and degenerate electron gases.

Evaporative cooling of polarized atoms is so far essential for the production of quantum degenerate gases [6]. It is driven by elastic collisions. At ultra-low temperature T, i.e. below a few millikelvin for lithium, collisions between bosons or distinguishable particles are predominantly s-wave collisions while Pauli exclusion prohibits s partial-waves of polarized fermions. In an ultra-cold gas of indistinguishable fermions the elastic collision rate diminishes proportional to T^{-2} which has recently been confirmed by De Marco *et al.* for ^{40}K [7]. Fermionic atoms can be cooled *sympathetically* by collisions in a mixture of different internal states [8,7] or of different species, yet to be implemented.

We intend to sympathetically cool fermionic ^{6}Li with the bosonic ^{7}Li isotope. This could produce not only a quantum degenerate Fermi gas but also a Bose-Einstein condensate of ^{7}Li in both HF ground states as well as a mixture of quantum degenerate gases of fermions and bosons [9]. One can also employ ultracold bosons to probe collisional properties of a degenerate Fermi gas [3].

Previously several groups have studied samples of two atomic species in a magneto-optical trap (MOT) [11]. In this article we describe the first realization of a MOT containing both fermionic and bosonic lithium and its optimization for sympathetic cooling. 4×10^8 ^{6}Li atoms and 9×10^9 ^{7}Li atoms are simultaneously confined. These numbers together with the density and temperature achieved should be sufficient to produce a Fermi gas with a Fermi temperature on the order of 10 μK in a harmonic magnetic trap of frequency $\overline{\omega}/2\pi = 400\,\mathrm{s}^{-1}$. The phase space density $\mathcal{D}= n_0\Lambda^3/f$ of unpolarized atoms (f internal states) with a peak density n_0 and temperature T is the number of identical atoms per cubic thermal DeBroglie wave length $\Lambda = (2\pi\hbar^2/mk_BT)^{1/2}$. The achieved phase space density in the two-isotope magneto-optical trap is 4×10^{-6} for ^{7}Li($f = 3$) and 0.8×10^{-6} for ^{6}Li($f = 2$). In single isotope traps, the number of fermions(1.5×10^9) exceeds the best previous realization of laser-cooled fermions by more than one order of magnitude [7]. The number of trapped ^{7}Li (1.8×10^{10}) is also a factor of 10 improvement [10].

In future experiments, this two isotope sample will be polarized and transferred into a magnetic trap. Bosonic lithium will be evaporatively cooled. Fermionic lithium thermalizes with the bosons via elastic collisions. Neglecting inelastic losses, all initially confined fermions should reach the quantum degenerate regime. In efficient evaporative cooling the phase space density $\mathcal{D}$ is increased by $\sim 10^6$ by decreasing the atom number by ~ 100 [6]. For sympathetic cooling this implies that N initially confined ^{7}Li atoms can sympathetically cool a sample of $N/100$ ^{6}Li atoms into the quantum degenerate regime ($\mathcal{D} \gg 1$). We therefore aim to maximize the number N of ^{7}Li atoms in the two-isotope trap while simultaneously confining at least $N/100$ ^{6}Li atoms. It is equally crucial that atoms thermalize quickly during the trap lifetime. Thus the initial elastic collision rate Γ_i between ^{7}Li atoms in the *mode-matched* and compressed magnetic trap must be maximized. For a linear trapping potential in three dimensions Γ_i can be related to quantities of the MOT as follows:

$$\Gamma_i \propto N^{4/9}{\mathcal{D}_i}^{5/9} \propto NT^{-5/6}\sigma^{-5/3} \qquad (1)$$

N is the number of trapped atoms, T is the temperature of the sample and σ the width of the gaussian density distribution $n(r) = N/(\sqrt{2\pi}\sigma)^3 \times exp(-r^2/2\sigma^2)$ in the MOT. We have optimized the laser-cooled sample of ^{7}Li with respect to Γ_i in presence of ^{6}Li.

In the experiment, the MOT is loaded from a Zeeman slowed lithium beam. ^{6}Li in the beam is enriched and has an abundance of about 20 %. Both isotopes

are slowed and confined in the MOT with 671 nm light near resonant with the D2 line, the $2S_{1/2} \rightarrow 2P_{3/2}$ optical transition. The isotopic shift for this transition is 10 GHz. Each isotope requires two frequencies to excite from the two HF ground states. The HF splitting is 803.5 MHz for ^{7}Li and 228.2 MHz for ^{6}Li. Hence simultaneous laser cooling of both lithium isotopes requires *eight* different laser frequencies: four frequencies for Zeeman slowing and four frequencies for magneto-optical trapping as shown in Fig. 1.

All frequencies are derived with acousto-optical modulators from two grating-stabilized external-cavity diode lasers based on 30 mW laser diodes. The lasers are frequency locked in saturated absorption to the D2-lines of ^{6}Li and ^{7}Li respectively. The slowing light is produced by geometrical superposition of the output of four injection seeded 30 mW laser diodes. Four trapping frequency components are geometrically superposed and 15 mW of this light is injected into a tapered semiconductor amplifier chip. After spatial filtering the chip produces up to 140 mW of trapping light containing the four frequency components in a gaussian mode at identical polarization as described in [12]. The intensity ratio of the frequency components in the trapping beams can be adjusted. This light is split up into six independent gaussian trapping beams, each with maximum peak intensity of $I_{max} = 6\,\mathrm{mW/cm^2}$, a $1/e^2$ intensity width of 3 cm and an apertured diameter of 2 cm. The MOT is operated in a 4 cm×4 cm×10 cm Vycor glass cell of optical quality $\lambda/2$. Background gas collisions limit the $1/e$ MOT lifetime τ to about 25 s.

The trapped atom clouds of both isotopes are separately observed in absorption imaging. For observation the trapping light and magnetic field are switched off abruptly. The induction limited $1/e$ decay time of the magnetic field is less than 50 μs. After free ballistic expansion with an adjustable time-of-flight between 150 μs and 7 ms the sample is illuminated for 80 μs by a probe beam. This probe excites either ^{7}Li from the F=2 ground state or ^{6}Li from the F=3/2 ground state to the $2P_{3/2}$ excited state manifold. The absorption shadow of the sample is imaged onto a charge-coupled device (CCD) camera. A separate repumping beam which is not projected onto the camera excites atoms in the other HF ground state to avoid optical pumping. The density distribution, atom number and temperature of the sample are obtained from absorption images for different ballistic expansion times.

Both isotopes are magneto-optically trapped in two steps: In the first step, *the loading phase*, the capture volume and velocity of the trap is large such that the number of trapped atoms is maximized. In the second step, *the compression phase*, the already trapped atoms are compressed in phase space such that the initial elastic collision rate Γ_i is maximized.

All four frequencies ν_{P7}, ν_{R7}, ν_{P6} and ν_{R6} of the MOT are exciting on the D2-line. We maximized the number of ^{7}Li atoms and ^{6}Li atoms in separate MOTs as well as the number of ^{7}Li atoms in the two-isotope trap. The maximization involved the detunings $\delta_{P7}, \delta_{R7}, \delta_{P6}, \delta_{R6}$ of the light components from the cooling and repumping transitions of the two isotopes (Fig.1), the intensities of all frequency components and the strength of the magnetic field of the MOT.

First, the atom number in separate *single-isotope* MOTs with only the two frequencies for the respective isotope present was optimized. We were able to capture up to 1.8×10^{10} ^{7}Li atoms and 1.5×10^9 ^{6}Li atoms. The atom number N, peak density n_0, temperature T and the respective detunings are listed in Tab.I. The atom number is accurate to within a factor of 2 and this dominates the uncertainty in the density determination. The temperature uncertainty is 0.2 mK. For both isotopes the atom number is maximized at large frequency detunings and equal intensities in both frequency components. The optimum magnetic field gradient B' along the symmetry axis of the magnetic quadrupole field of the MOT is about 35 G/cm for both isotopes. The MOT was operated at maximum intensity $I_{max} = 6\,\mathrm{mW/cm^2}$ in each of the six beams.

In the ^{7}Li trap, at low atom number ($\leq 10^9$) the temperature is the Doppler temperature (1.1 mK at $\delta_{P7} = -8\Gamma$), as shown in Fig 2. At large atom numbers, for 5×10^9 to 2×10^{10} trapped atoms, the temperature is 1.5(2) mK and nearly constant while the density typically saturates at n_0=$3 \times 10^{11}\,\mathrm{cm^{-3}}$. In this regime the number of trapped ^{7}Li atoms is limited by loss due to inelastic radiative escape (RE) or fine structure changing (FS) collisions. In steady-state, the slow atom flux $\mathcal{F}$= $2 \times 10^9\,\mathrm{s^{-1}}$ is balanced by the trap loss according to

$$\mathcal{F} = N/\tau + \beta n_0 N/\sqrt{8} \qquad (2)$$

τ = 25 s is the background gas limited lifetime of the MOT. The two-body loss coefficient $\beta = 6 \times 10^{-13}\,\mathrm{cm^3/s}$ was experimentally determined and is consistent with previous studies of trap loss in a ^{7}Li MOT [13].

In ^{7}Li the HF splitting between the F′=3 and the F′=2 excited states is 1.6 Γ and in ^{6}Li, 0.5 Γ between the F′=5/2 and the F′=3/2 excited states, where Γ = 5.9 MHz is the natural width of the lithium D-lines. Despite the inverted excited state HF structure of both lithium isotopes, the small HF splitting leads to off-resonant excitation of the F=2→F′=2 transition in ^{7}Li, and the F=3/2→F′=3/2 transition in ^{6}Li and frequent decay into the lower HF ground state. The repumping light component is therefore of equal importance as the principal trapping light. In fact, we only obtained a MOT with the repumping light also in a six-beam MOT configuration. This is not required in MOTs of other alkalis with larger HF splitting, such as Cs, Na or Rb.

For the two-isotope trap, the ^{6}Li repumping transition F=1/2→F′=3/2 is about 7(3) Γ to the blue of the

F=2→F′=1 resonance in the D1 line of ^{7}Li. If both lithium isotopes are simultaneously confined, the ^{6}Li repumping light component ν_{R6} frequently excites this *non-cooling* transition and significantly weakens the confinement of the trap for ^{7}Li. This leads to smaller number of trapped ^{7}Li atoms in the presence of ^{6}Li light. We reduce this harmful effect by detuning towards the D1 resonance while reducing the intensity. The coincidence could also be avoided by repumping ^{6}Li on the D1 line instead. Aside from the light induced trap loss we do not observe mutual effects due to the presence of both isotopes (such as collision induced trap loss, heating or a modification of the spatial distribution).

As discussed in the introduction, for efficient sympathetic cooling in subsequent stages of the experiment we require about 100 times less precooled ^{6}Li atoms than ^{7}Li atoms. We decrease the intensity of ^{6}Li light in the two-isotope trap in order to reduce the ^{7}Li trap loss. This maximizes the number of ^{7}Li atoms at the cost of less ^{6}Li atoms. We are able to confine 9×10^9 ^{7}Li atoms together with 4×10^8 ^{6}Li atoms. This result was obtained with an intensity relation between the four frequency components ν_{P1}, ν_{R1}, ν_{P2} and ν_{R2} of $8:8:2:1$ and a magnetic field gradient $B' = 35\,\mathrm{G/cm}$. N, n_0, T and the respective detunings for the two-isotope MOT are listed in Tab. I.

After loading the trap it is possible to further compress the sample in phase space and maximize the initial elastic collision rate Γ_i by changing the laser parameters for the duration of a few milliseconds. From Eq.1 follows that in case of *no* loss of atoms during compression a maximization of Γ_i also maximizes $\mathcal{D}_i$. For the compression, we optimize Γ_i with respect to the total laser intensity and the frequency detunings δ_{P6}, δ_{P7}, δ_{R6}, δ_{R7} while keeping B' constant at $35\,\mathrm{G/cm}$. We compress the single-isotope MOTs as well as the two-isotope sample. For sympathetic cooling we are especially interested in maximizing Γ_i for ^{7}Li in the presence of ^{6}Li. As shown in Tab. II, decreasing δ_{R7}, i. e. detuning ν_{P7} further to the red of the transition, and increasing δ_{P7} towards resonance while reducing the overall laser intensity to $0.3\,I_{max}$=$1.8\,\mathrm{mW/cm^2}$ results in a 40% drop in temperature and increases the density by 70 %. 30 % of the initially confined atoms are lost during the first 3 ms of compression. This loss is either due to FS- and RE-collision induced heating during the initial compression stage or due to a loss of parts of the cloud as a consequence of an abrupt change of laser frequencies (see Fig. 3). According to Eq.1 compression increases Γ_i by 60%. After compressing the two-isotope trap for 3 ms, we obtain a maximum of 6×10^9 ^{7}Li atoms at a peak density of $4 \times 10^{11}\,\mathrm{cm^{-3}}$ and a temperature of 0.6 mK together with ^{6}Li at a density 6.5×10^{10} $\mathrm{cm^{-3}}$ and a temperature of 0.7 mK. Aside from the initial loss during the first few milliseconds, the $1/e$ trap lifetime also decreases to about 30 ms for both isotopes.

Fig.3 shows the typical temporal dynamics of atom number, width and temperature of the ^{7}Li compressed MOT (CMOT) for the first 6.5 ms of compression. Γ_i and $\mathcal{D}_i$ reach a maximum after about 3 ms. The CMOT is rather insensitive to the repumping frequency ν_{R7}: detuning by $2\,\Gamma$ above and below the optimized value of $5.8\,\Gamma$ decreases Γ_i by less than 25%. The CMOT is much more sensitive to the detuning ν_{P7} of the trapping light. We optimized Γ_i with respect to the duration t of the compression phase and the detuning. The maxima of Γ_i and $\mathcal{D}_i$ remain at a constant value for $t \geq 3$ ms but shift to different detuning parameters with increasing CMOT duration.

To summarize, we showed that it is possible to trap about 6×10^9 ^{7}Li atoms together with 3×10^8 ^{6}Li atoms in the two-isotope MOT at at phase space densities of $\sim 10^{-6}$. These results are comparable to results achieved with single isotopes of Na or Cs in a *dark* SPOT [14]. In combination with a strong confining magnetic trap we expect an initial elastic collision rate well above $10\,\mathrm{s^{-1}}$, despite the small triplet scattering length of 1.4 nm (^{7}Li-^{7}Li) and 2.0 nm (^{6}Li-^{7}Li) [15]. This can lead to the production of quantum degenerate Bose and Fermi gases of lithium by forced evaporation and sympathetic cooling within a few seconds.

We are grateful for experimental assistance of Fabrice Gerbier. We thank C. Cohen-Tannoudji and J. Dalibard for discussions and Kirk Madison for careful reading of the manuscript. M.-O. M. and F. S. are supported by a Marie-Curie Research fellowship of the EC and a doctoral fellowship from the DAAD(HSP 3) respectively. This work was partially supported by CNRS, Collège de France, DRED, and the EC (TMR Network No. ERB FMRX-CT96-0002). Laboratoire Kastler Brossel is *Unité de recherche de l'Ecole Normale Supérieure et de l'Université Pierre et Marie Curie, associée au CNRS.*

[1] M.H. Anderson *et al.*, Science **269**, 198 (1995); K.B. Davis *et al.*, Phys. Rev. Lett. **75**, 3969 (1995); C.C. Bradley, C.A. Sackett, and R.G. Hulet, Phys. Rev. Lett. **78**, 985 (1997); D.G. Fried *et al.*, Phys. Rev. Lett. **81**, 3811 (1998).

[2] J.M.K.V.A. Koelman *et al.*, Phys. Rev. Lett. **59**, 676 (1987); A. Imamoglu and L. You, Phys. Rev. A **50**, 2642 (1994); J. Javanainen and J. Roustekoski, Phys. Rev. A **52**, 3033 (1995); B. DeMarco and D.S. Jin, Phys. Rev. A **5**, R4267 (1998).

[3] G. Ferrari, Phys. Rev. A **59**, R4125 (1999).

[4] T. Busch *et al.*, Europhys. Lett. **44**, 1 (1998).

[5] A.J. Leggett, J. Phys. C **7**, 19 (1980); H.T.C. Stoof *et al.*, Phys. Rev. Lett. **76**, 10 (1996); M.A. Baranov, Y. Kagan and M.Y. Kagan, JETP Lett. **64**, 301 (1996); A.G.W. Modavi, A.J. Leggett, J. Low. Temp. Phys. **109**, 625 (1998).

[6] W. Ketterle and K.J. van Druten, in *Advances in Atomic, Molecular, and Optical Physics*, edited by B. Bederson and H. Walther (Academic Press, San Diego, 1996), No.37, p.181.
[7] B. DeMarco *et al.*, Phys. Rev. Lett. **82**, 4208 (1999).
[8] C.J. Myatt *et al.*, Phys. Rev. Lett. **78**, 586 (1997);
[9] K. Moelmer, Phys. Rev. Lett. **80**, 1804 (1998); E. Timmermans and R. Côté, Phys. Rev. Lett. **80**, 3419 (1998); W. Geist, L. You, and T.A.B. Kennedy, Phys. Rev. A **59**, 1500 (1999).
[10] U. Schünemann *et al.*, Opt. Comm. **158**, 263 (1998).
[11] W. Süptitz *et al.*, Opt. Lett. **19**, 1124 (1994); M.S. Santos *et al.*, Phys. Rev. A **52**, R4340 (1995); G.D. Telles *et al.*, Phys. Rev. A **59**, R23 (1999); J.P. Shaffer, W. Chalupczak, and N.P. Bigelow, Phys. Rev. Lett. **82**, 1124 (1999); U. Schlöder *et al.*, EPJ D (in print).
[12] G. Ferrari, M.-O. Mewes, F. Schreck, and C. Salomon, Opt. Lett. **24**, 151 (1999).
[13] J. Kawanake, K. Shimizu, H. Tanaka, F. Shimizu, Phys. Rev. A **48**, R883 (1993); N.W.M. Ritchie *et al.*, Phys. Rev. A **51**, 961 (1995).
[14] W. Ketterle *et al.*, Phys. Rev. Lett **70**, 2253 (1993).
[15] E.R.I. Abraham, W.I. McAlexander, C.A. Sackett and R.G. Hulet, Phys. Rev. A **55**, R3299 (1997).

	single isotope MOT		two isotope MOT	
	^{7}Li	^{6}Li	^{7}Li	^{6}Li
N	1.8×10^{10}	1.5×10^9	9×10^9	4×10^8
n [cm^{-3}]	3×10^{11}	1.0×10^{11}	2.5×10^{11}	5×10^{10}
T [mK]	1.5	0.7	1.0	0.7
$\delta_{P7,6}$ [Γ]	-8.0	-2.7	-8.0	-2.7
$\delta_{R7,6}$ [Γ]	-5.8	-5.1	-5.8	-5.1

TABLE I. Comparison of atom number N, peak density n_0, temperature T and frequency detunings for the single-isotope and two-isotope MOT.

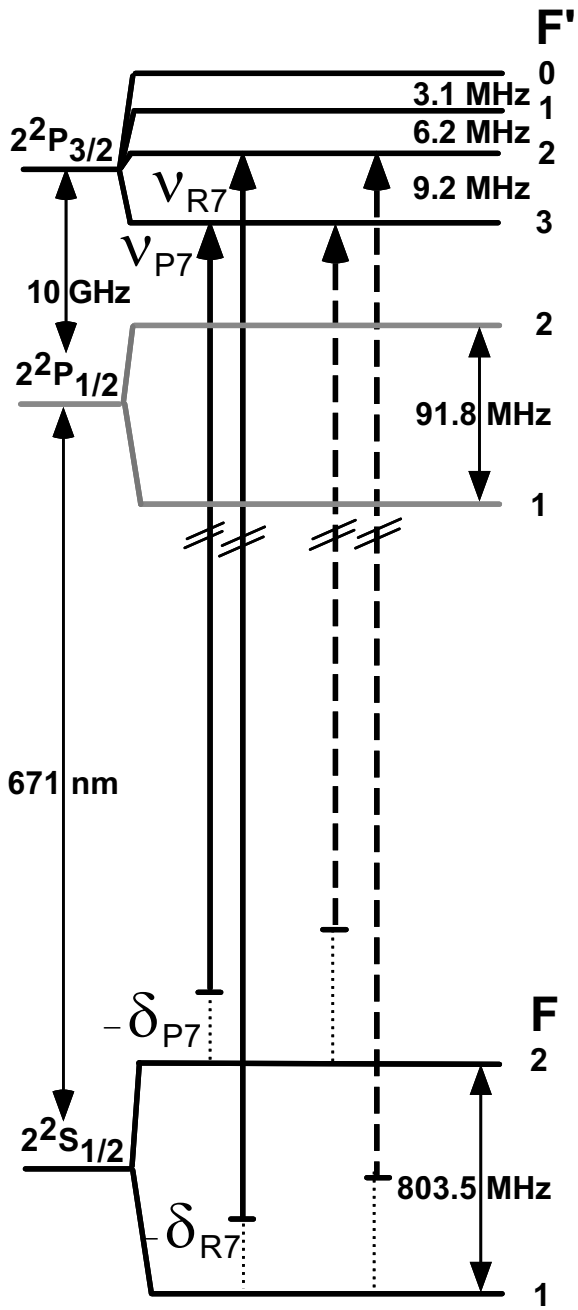
	single isotope CMOT		two isotope CMOT	
	^{7}Li	^{6}Li	^{7}Li	^{6}Li
N	7×10^9	5×10^8	6×10^9	3×10^8
n [cm^{-3}]	4×10^{11}	1.5×10^{11}	4×10^{11}	6.5×10^{10}
T [mK]	0.6	0.4	0.6	0.7
$\delta_{P7,6}$ [Γ]	-3.0	-2.7	-3.0	-2.7
$\delta_{R7,6}$ [Γ]	-9.0	-2.7	-9.0	-5.8

TABLE II. Comparison of atom number N, peak density n_0, temperature T and frequency detunings for the single-isotope and two-isotope compressed MOT.

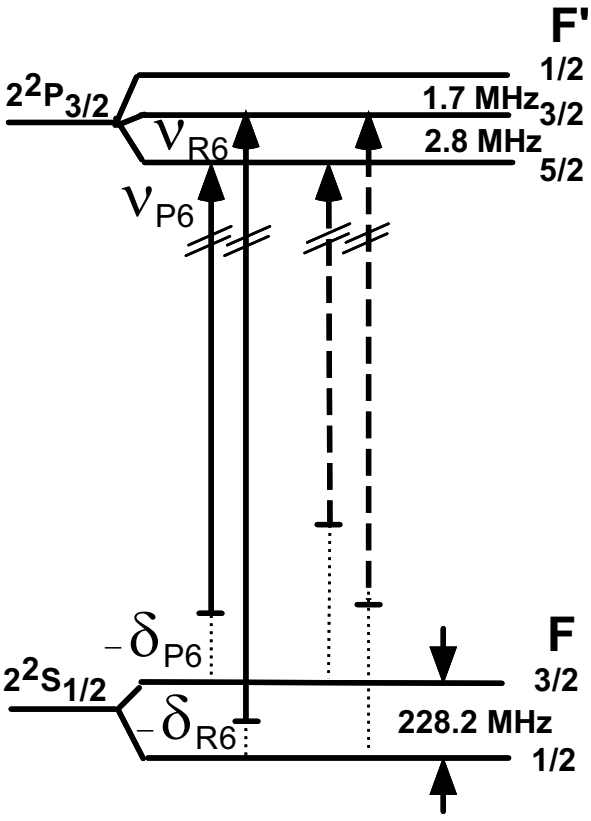
FIG. 1. Frequencies employed to slow (dashed arrows) and magneto-optically trap (solid arrows) both lithium isotopes. The detunings of the frequencies from the respective resonances are marked with a dotted line. The detuning of the slowing light from the respective zero magnetic field transitions for ^{7}Li is -426 MHz and -447 MHz for ^{6}Li.

FIG. 2. Temperature T, 1D *rms* width σ and peak density n_0 in a ^{7}Li MOT versus atom number N. N was varied by changing the loading time. In b) the width along the symmetry axis z of the magnetic field (solid data points) is $\sim 40\%$ smaller than in the radial direction (hollow points) as expected from a simple MOT model($1/\sqrt{2}$).

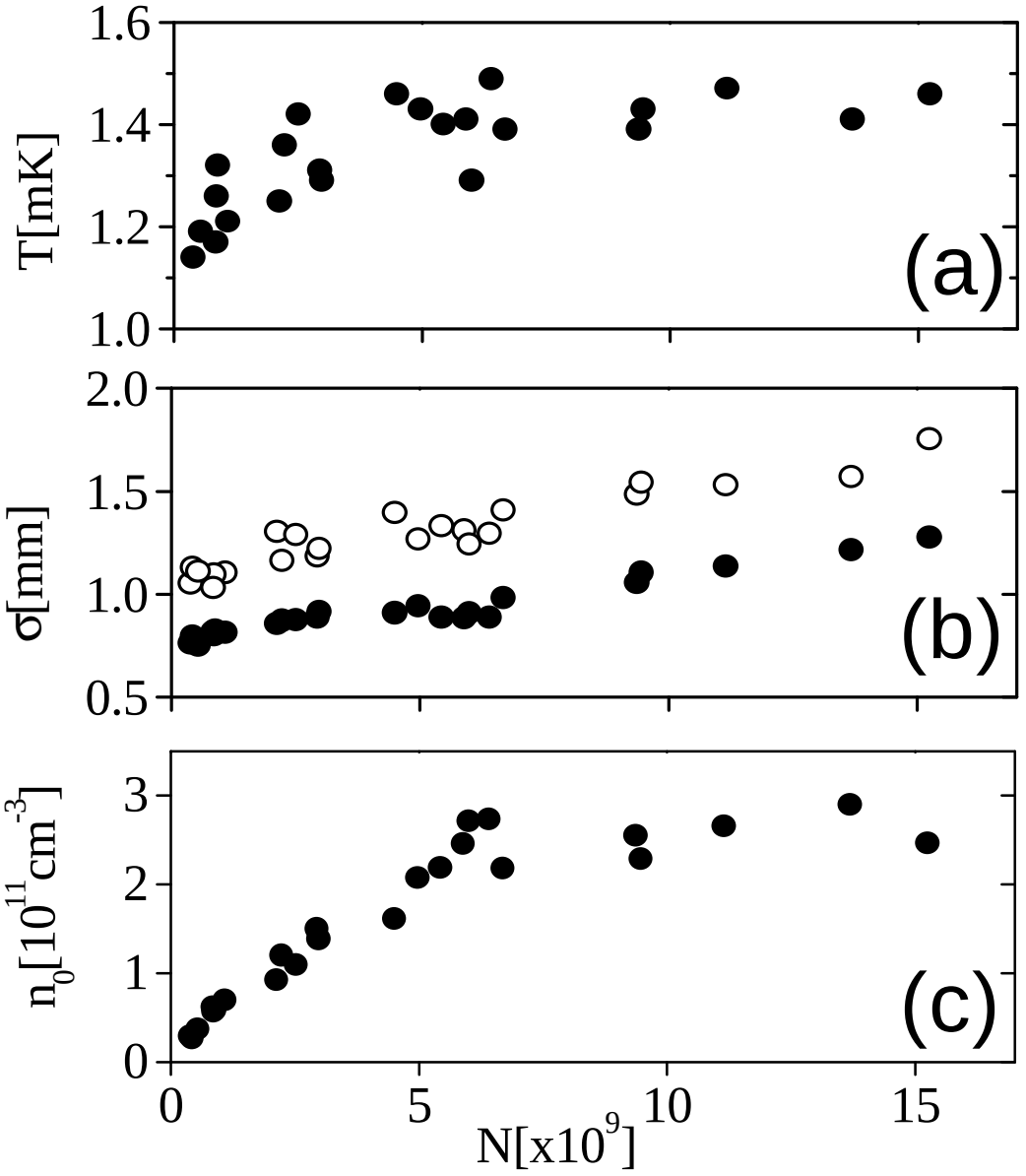
FIG. 3. Temporal dynamics of the compression phase of a ^{7}Li MOT. Atom number N, temperature T, and *rms* width σ_z after abrupt change of the laser parameters at $t = 0$.

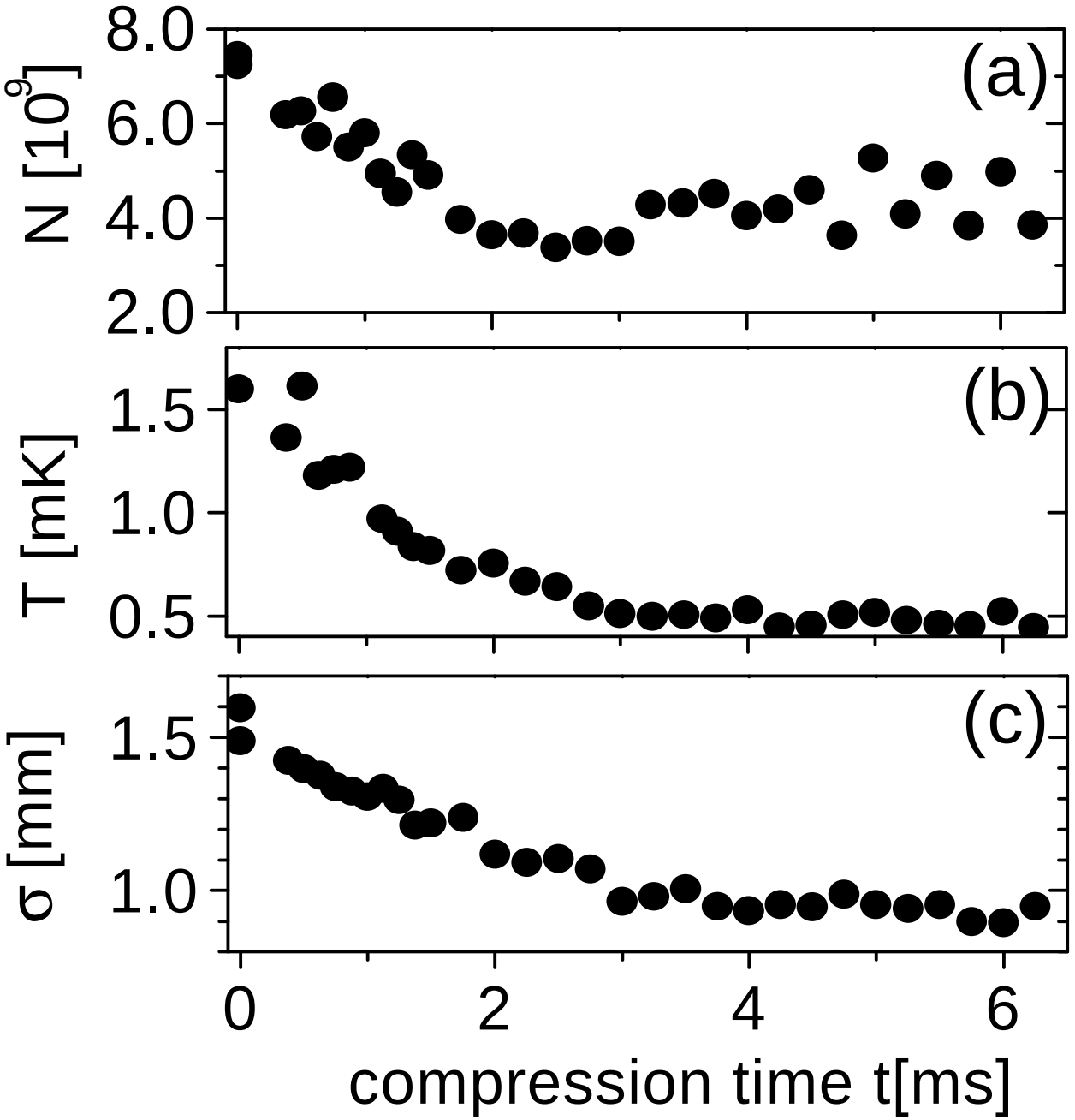


Lithium-7



Lithium-6


1.6
1.4
1.2
1.0
T[mK]
(a)
2.0
1.5
1.0
0.5
σ[mm]
(b)
3
2
1
0
$n_0[10^{11}cm^{-3}]$
(c)
0
5
10
15
$N[x10^9]$


8.0
6.0
4.0
2.0
N [10^9]
(a)
1.5
1.0
0.5
T [mK]
(b)
1.5
1.0
σ [mm]
(c)
0
2
4
6
compression time t[ms]